ELECTRON HOLOGRAPHY MICROSCOPY AND ITS APPLICATION TO THE OBSERVATION OF MAGNETIZATION CONFIGURATION

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Abstract— Electron holography microscopy is used to investigate the recorded magnetization configurations in a Co-Cr single medium. The lines of magnetic force straying from the surface of the medium can be directly observed with the period of recorded bit length. Digital image processing techniques enable visualization of extremely weak magnetic fields at ultra high recording densities, up to 300 kFCI. Using these techniques, it is found that the recorded magnetization at 300 kFCI is as large as 160 kA/m, indicating that perpendicular magnetic recording prevails as linear bit density becomes higher.

INTRODUCTION

Recent increases in magnetic recording density rely mainly on the use of magnetic thin film media, such as Co-Cr-Ta sputtered film or metal-evaporated (ME) tape. The use of such materials increasingly demands more precise information on the microstructure and magnetic behavior of magnetic thin films from the microscopic point of view. A systematic research on magnetic thin films from its microstructure to its magnetism, is therefore, desired much more than before.

Electron holography microscopy [1] is a powerful tool for observing the magnetization configuration in the micro region of thin films because it has high spatial-resolution and the capacity to measure quantitatively the intensity of magnetic flux. We have used this technique for investigating the magnetization configuration in obliquely incident Co layers [2] and Co-Cr single layers [3]-[5]. Hence, if the observation of recorded magnetization configuration in Co-Cr double layers, which is now in progress in cooperation with Drs. Y. Maeda and T. Okubo of NTT, and Dr. S. Tsukahara of ULVAC JAPAN, is successful, many useful and fundamental results are expected.

In this paper, the principle of electron holography is described briefly and the results [3]-[5], which were obtained by the observation of the magnetic flux straying from the perpendicularly recorded Co-Cr single layers, are reviewed.

PRINCIPLE OF ELECTRON HOLOGRAPHY

The principle underlying the observation of magnetic flux by electron holography is described schematically in Fig. 1. Consider an electron beam passing through a magnetic film and focused at one point. The phase difference ($\Delta \Phi(P_1, P_2)$) between two points ($P_1, P_2$) below the specimen due to the vector potential ($A$) generated by the magnetic specimen is given by

$$\Delta \Phi(P_1, P_2) = -\frac{e}{\hbar} \int A \, dr = -\frac{e}{\hbar} \int B \, ds \quad (1)$$

Where, $A$ is the vector potential and $B$ is the magnetic induction. $-e$ is the charge of an
electron and \( \pi = h/2\pi \), where \( h \) is Planck's constant. The two integrals are performed along two electron trajectories \( (r) \), and the surface \( (s) \) enclosed by the trajectories.

From this equation the following results are obtained: (1) the phase difference is equal to zero if \( P_1 \) and \( P_2 \) lie along a line of magnetic force in the specimen because \( \mathbf{B} \, ds = 0 \); (2) the phase difference is just one wavelength \( (2\pi) \) when two trajectories contain the magnetic flux of \( h/e \) \( (=4.1\times10^{-15} \text{ Wb}) \). Therefore, if a contour map of the electron wave front is visualized, the lines of magnetic force in the specimen can be directly observed as contour lines. Also the intensity of magnetic field can be measured quantitatively because neighboring contour lines contain a constant flux of \( h/e \).

Observation of the contour map is performed in the two stages: formation of a hologram and optical reconstruction. The electron hologram formation is shown in Fig. 2. The electron hologram is formed by field-
using the comparison beam that is parallel to the object beam.

This holographic technique makes it possible to obtain phase-amplified interference images having a factor n (integer). Thus the technique enables observation of details of magnetic flux, even though phase differences are less than $2\pi$. The recently developed technique, 'fringe scanning interferometry', using digital image processing at the optical reconstruction stage, allows us to visualize extremely weak magnetic fields [6].

EXPERIMENTAL PROCEDURE

The Co-Cr single layers were prepared with vacuum evaporation on polyimide base film. A Ge layer was used in order to promote the preferential c-axis orientation of the Co-Cr layer. Magnetic recordings were made using a MIG type magnetic head with a gap length of 0.25 μm. The recorded media were sliced from top to bottom and vice versa with a microtome, resulting in a thickness of approximately 0.1 μm, as shown in Fig. 4. The magnetic properties were measured with a vibrating magnetometer (VSM). They are listed in Table 1.

RESULTS AND DISCUSSION

The magnetic lines of leakage flux straying from the Co-Cr layer, perpendicularly recorded at 100 kFCI, are shown in Fig. 5. The lines of magnetic force can be observed clearly at both the front and rear surfaces, although the number at the rear is a little smaller than at the front. This result clearly shows that the recorded magnetization penetrates the whole film thickness of 0.35 μm, as shown schematically in Fig. 6, in spite of the relatively short bit length of 0.25 μm. This result also indicates that the recorded depth of perpendicular magnetic recording is deeper than that of longitudinal recording, which is thought to be $\lambda/4$. Here, $\lambda$ is a recorded wave length.

Table 1 Specimens properties

<table>
<thead>
<tr>
<th>specimen</th>
<th>Ms (kA/m)</th>
<th>$H_{c,\perp}$ (kA/m)</th>
<th>$H_{c,\parallel}$ (kA/m)</th>
<th>S.L</th>
<th>S.</th>
<th>Co-Cr</th>
<th>protective layer</th>
<th>slice</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>420</td>
<td>49</td>
<td>16</td>
<td>0.15</td>
<td>0.11</td>
<td>0.35</td>
<td>0.005</td>
<td>0.08</td>
</tr>
<tr>
<td>B</td>
<td>250</td>
<td>52</td>
<td>14</td>
<td>0.18</td>
<td>0.08</td>
<td>0.20</td>
<td>0.015</td>
<td>0.08</td>
</tr>
</tbody>
</table>
The boundaries of adjacent recorded magnetization regions are imagined to be tilted as shown in Fig. 6. The possible causes of the phenomenon could be: (1) the influence of the magnetic field of the ring type head having a strong in-plane component; (2) the phase difference due to the inclination of the hologram at the optical reconstruction stage. The direct observation of the inside of the Co-Cr layers will clarify the recorded magnetization configuration. (The acceleration voltage (45 keV) of the electron microscope was too low to observe the film inside.)

The numbers of the magnetic lines also give us quantitative information about the recorded magnetization in the Co-Cr medium. The maximum recorded magnetization was calculated to be 200±20 kA/m, although the numbers were different depending on the bit. This value is about three times the residual magnetization measured with VSM, showing clearly that the demagnetization factor is reduced by the perpendicular magnetization configuration. The measured recorded magnetization is compared with the sheared residual magnetization by the demagnetizing factor of 0.19 which was calculated from the aspect ratio of recorded bit length (0.25 μm) to film thickness (0.35 μm), as shown in Fig. 7. The sheared M-H loop has a residual magnetization of 250 kA/m. This value is thought to be approximately the ideal recorded magnetization which has not suffered from any recording loss. The ratio of the recorded magnetization to the sheared residual magnetization is 0.75 to 0.90, meaning that the magnetization recorded in contact with a head is fairly close to the sheared residual magnetization [3].

Figure 8 shows the interference micrographs of leakage flux above the Co-Cr medium recorded at 300 kFCI (a) and at 200 kFCI (b). At such a high recording density, the intensity of the leakage flux becomes so extremely weak that the sensitivity is insufficient for quantitative analysis. However, ‘fringe scanning interferometry’ using digital...
image processing techniques at the optical stage allowed us to amplify phase-difference up to 100 times so that we could obtain precisely subfringe information [6]. The phase-amplification factor of Fig. 8(a) is as large as 60. The micrographs succeeded in visualizing extremely weak magnetic flux. The leakage flux from the rear side could not be observed, indicating that the recorded magnetization in the layers did not penetrate through the whole of the film thickness at such a short bit length. Fig. 8(c) represents the cross-sectional structure of the Co-Cr layer. The TEM image was observed using another electron microscope which was operated with an acceleration voltage of 200 keV. Although the columnar boundaries were not clear, the columnar diameter was found to range between 30 and 55 nm. It should be noted that magnetic recording can be performed, even though the recorded bit length gets close to the columnar diameter. This result is thought to suggest that magnetic phase separation within a column, Co-rich regions and Cr-rich regions [7],[8], play an important role for recording at ultra high density.

The magnetic field vector component of the specimen recorded at 300 kFCI was calculated from the phase data. Figure 9 shows the perpendicular component of the leakage field using a gray scale image. White means positive (upward vector) and black means negative (downward vector). The intensity of the leakage field is illustrated in Fig. 9. The intensity oscillates along the horizontal axis with the period of recorded bit length. The amplitude decreases as the distance from the surface increases. The dependence of the amplitude on the distance (d) is shown in Fig. 10. This shows that the leakage flux decreases at the rate of $-54 d/\lambda (dB)$, which agrees well with the theoretical value. The amplitude at the surface is extrapolated to be 160 kA/m, which gives the equivalent recorded magnetization. In this case, the aspect ratio of the bit length (0.085 \(\mu\)m) to the film thickness (0.2 \(\mu\)m) leads to a demagnetizing factor less than 0.1. Hence, the recorded magnetization is expected to be almost

![Fig. 8 Interference micrographs of magnetic flux straying above a Co-Cr medium recorded at 300 kFCI and at 200 kFCI(b). Transmission electron micrograph and the diffraction pattern of sliced specimen (c).](image)

![Fig. 9 Distribution of magnetic field intensity in the vertical direction to the medium surface (300 kFCI). Changes in the vertical component of the magnetic field at a distance of 10(a-a), 30(b-b), and 50(c-c) nm from the surface are shown by lines of a, b, c, respectively.](image)
equal to the saturation magnetization (254 kA/m), if recording loss does not occur. The deviation of the actual value from the ideal is thought to result from insufficient recording, leading to insufficient penetration through the film thickness.

SUMMARY

The principle of electron holography microscopy and its application to magnetic recording were reviewed. The lines of magnetic force straying from the front and rear surfaces were directly observed using electron holography microscopy. Moreover, the quantitative information on the intensity of the magnetic field allowed us to precisely evaluate the recorded magnetization on a Co-Cr medium, which would be difficult using conventional methods such as Lorentz microscopy. The recorded magnetization in a Co-Cr medium with a ring type head was strong enough even at ultra high recording densities of 300 kFCl (bit length of 0.085 μm), implying that perpendicular magnetic recording prevails over longitudinal recording in a high linear density recording.

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